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TECHNICAL REPORT ARLCD-TR-81023

**DETERMINATION OF MINIMUM NONPROPAGATION DISTANCES  
OF VARIOUS CONFIGURATIONS OF 155MM  
M549 HERA PROJECTILES**

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test plans and coordination of the testing program were accomplished by the ARRADCOM Resident Operations Office, National Space Technology Laboratories (NSTL) Station, Mississippi. The Hazardous Range Support Unit, Computer Science Corporation, NSTL, was responsible for the field testing and basic data collection.

20. ABSTRACT (Cont)

applicable to other similar facilities. The test results indicated that the minimum nonpropagation distance for single projectiles is 1.5 meters (5.0 feet) unshielded and 8.9 centimeters (3.5 inches) if a 7.6 centimeter (3.0 inch) diameter aluminum bar (6061-T6) is utilized as a shield between projectiles. The nonpropagation spacing between pallets of eight projectiles is 3.1 meters (10.0 feet) when a shielding arrangement consisting of two of the aforementioned aluminum bars is aligned with the projectiles on each end of the pallets.

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## SUMMARY

The safe separation testing distance of the 155mm M549 HERA Projectiles, loaded with 7.3 kg (16.0 lb) of Composition B, was requested by the Project Manager for Munition Production Modernization and Expansion in support of the Iowa Army Ammunition Plant (AAP). After a review of the Load-Assemble-Pack (LAP) operations at the Iowa AAP, it was determined that two projectile configurations warranted safe separation distance studies: (1) single projectiles positioned vertically and (2) pallets of eight projectiles in a 2 by 4 matrix. A program to determine the necessary minimum non-propagation distance was drafted by ARRADCOM and conducted at the National Space Technology Laboratories (NSTL) Station, Mississippi.

The test program was conducted in two distinct portions, each simulating actual LAP plant operational conditions. Each portion was further subdivided into unshielded and shielded test sections, with exploratory tests being conducted for all test sections and confirmatory tests being conducted when necessary.

The first program consisted of an unshielded single projectile test which included a total of 40 tests (14 exploratory and 26 confirmatory). The results confirmed the safe separation non-propagation distance of 1.5 m (5.0 ft) with an upper limit of 6.72 percent probability of propagation at the 95 percent confidence level.

The second program section was the shielded single projectile tests, utilizing a 7.6-cm (3.0-in) diameter aluminum (6061-T6) rod positioned vertically in a straight line halfway between the projectiles. A total of 29 tests (4 exploratory and 25 confirmatory) were conducted, resulting in the confirmation of the safe separation non-propagation distance of 8.9 cm (3.5 in) with an upper limit of 6.85 percent probability of propagation at the 95 percent confidence level.

The third program section was the unshielded palletized projectile tests. After four tests, the analysis of the fragment damage to the acceptor projectile indicated the potential of detonation propagations for distances in excess of 9.1 m (30.0 ft). This program section was subsequently discontinued.

The fourth and final program section was the shielded palletized projectile tests, consisting of a series of 48 tests (15 exploratory and 33 confirmatory). The confirmatory tests utilized a shielding arrangement consisting of two 7.6-cm

(3.0-in) diameter aluminum (6061-T6) bars on each end of the pallets which were aligned with the projectile centerlines. The results indicated a safe separation non-propagation distance of 3.1 m (10.0 ft) with an upper limit of 4.8 percent probability of propagation at the 95 percent confidence level.

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## INTRODUCTION

### Background

Presently, an Army-wide modernization program is upgrading existing facilities, and developing new explosive manufacturing and Load-Assemble-Pack (LAP) facilities. This programmed effort will enable the U.S. Army to achieve increased production cost efficiency with improved functional safety of the man/item relationship. Furthermore, greater flexibility to provide manufacturing facilities for future weaponry systems within existing facilities will be available. As an integral part of this program, the Energetic System Process Division, Large Caliber Weapon Systems Laboratory, ARRADCOM, Dover, New Jersey, is engaged in the continuous development of safety criteria as an activity entitled "Safety Engineering in Support of Ammunition Plants". This program includes safe separation (non-propagation) distance studies of munition end-items as well as bulk in-process explosive materials. The criteria, developed within the auspices of this program, will be utilized as part of the basis for the design of all explosive production installations due for modernization and will be available for reference purposes to Privately-Owned and Privately-Operated (POPO) plants engaged in ordnance manufacturing operations.

The activities described in this report will provide safety criteria data to specifically support facility modernization provisions in the 155mm M549 HERA Projectile LAP areas at the Iowa AAP. The aforementioned safety criteria will also be applicable to other operating LAP facilities. A test program was developed and implemented to simulate the Iowa LAP facilities producing the 155mm M549 HERA Projectile.

### Objective

The primary objective of this project segment was to determine, by experimental testing, the safe non-propagation separation distance between various configurations of 155mm M549 HERA Projectiles during transport between LAP operations on continuous feed conveyor systems. The data derived from this project segment will be utilized to establish criteria for unit spacing on conveyors, conveyor speeds, and production rates for the manufacture of 155mm M549 HERA Projectiles.

The test program consisted of two portions, each utilizing an exploratory phase and an ensuing confirmatory phase to establish statistical confidence in the resultant safe separation

distances. The first portion utilized single 155mm M549 HERA Projectiles in a line, raised above terrain level to simulate the conveyor system's stand-off distance. The second portion utilized pallets containing eight 155mm M549 HERA Projectiles arranged in a 2 by 4 matrix, again in a line and raised above the terrain level to simulate the conveyor system's stand-off distance. The second portion of the test, designed with pallets of eight projectiles, utilized loading funnels filled with Composition B inserted into each projectile.

#### Criteria

The testing of both portions of the 155mm M549 HERA Projectile program segment was conducted to simulate accurately the actual LAP plant conditions. The only acceptable criteria for determining the safe separation distance was the non-propagation of the donor projectile (initiated charge) detonation to the adjacent acceptor projectiles. It should be noted that measured distances are centerline to centerline between adjacent single projectiles, and edge to edge between adjacent pallets containing eight projectiles.

## TEST CONFIGURATION

### General

Testing of the 155mm M549 HERA Projectile to determine the appropriate safe non-propagation separation distance between donor and acceptor projectiles was completed in December 1979. The program ran for a comparatively lengthy period due to continuous revisions and additions to the initial test plan; specifically, free air vs. shielded projectile test and single projectile vs. pallets of 8-projectile tests. All testing was conducted at the National Space Technology Laboratories (NSTL) Station, Mississippi, under the auspices of the ARRADCOM Resident Operations Office in conjunction with the Hazards Support Unit of the Computer Science Corporation.

As mentioned, the test program consisted of two distinct portions, further subdivided each into two test sections, with an exploratory test phase and a confirmatory test phase being performed within each section. The first program portion consisted of testing single 155mm M549 HERA Projectiles. Within this single projectile program portion, the testing was subdivided into the two mentioned sections: (1) free air tests and (2) tests with barriers or shields between the projectiles. In both cases, exploratory and confirmatory test phases were conducted to firmly establish the minimum safe non-propagative separation distance between single projectiles. The second program portion consisted of testing pallets, each containing eight 155mm M549 HERA Projectiles arranged in a 2 by 4 matrix. Similarly, the testing was subdivided into free air tests and tests with barriers or shields between the pallets of projectiles. As in the first program portion, both exploratory and confirmatory test phases were conducted for each section to firmly establish the minimum safe non-propagation separation distance between pallets of projectiles.

### Test Specimen

The test specimen utilized for this study program was the unfuzed 155mm M549 HERA Projectile with the lifting plug, spacer, supplementary charge, and liner removed from the nose cavity of the projectile (fig. 1). The projectile consists of two major component parts: (1) a warhead assembly loaded with 7.26 kg (16.0 lb) of Composition B high explosive and (2) a solid propellant rocket motor assembly. The two component assemblies are joined together by a threaded interface to externally form a continuous low drag aerodynamic contour. A rotating band

encircles the assembled projectile near the base end, approximately at the center of the rocket motor assembly. A "rocket-off" cap is threaded into the base of the motor assembly and is either left in-place during projectile firing as a conventional projectile (rocket motor not utilized) or is removed when a rocket-boosted assist is required for extended range. The rocket motor assembly contains a total of 3.18 kg (7.0 lb) of solid rocket propellant arranged in two segmented grains (three segments per grain). Each of the three segments of the forward grain contains an ignition pellet. The nozzle of the rocket motor is recessed into the center of the boat-tail base of the projectile and, when emerged, provides thrust along the longitudinal axis of the projectile.

The 155mm M549 HERA Projectile is 85.80 cm (33.78 in) in maximum length (without lifting plug or fuze) and has a maximum diameter at the rotating band of 15.80 cm (6.22 in). The average total projectile weight is 43.55 kg (96.0 lb). Arranged pallets of eight projectiles weigh 376.5 kg (830 lb), measure 33.72 cm (13.63 in) by 68.91 cm (27.13 in) by 98.43 cm (38.75 in) high, and have a cubic displacement of 0.27 m<sup>3</sup> (9.5 ft<sup>3</sup>).

The projectiles were all oriented vertically (nose up) at detonation, tested one at a time, and set in pallets of eight (arranged in 2 by 4 matrices). The tests involving the palletized projectiles utilized loading funnels, placed into the top (nose end) of each projectile, for pour casting the high explosive into the projectile cavity. Both the cavity and funnel were fully loaded for the test detonation (fig. 2).

#### Test Arrangement

Each test layout, during both the single projectile tests and the pallet of 8-projectile tests, utilized one donor specimen and two acceptor specimens raised off the ground to simulate the conveyor's height above the inter-building tunnel floor. The center specimen served as the donor and the two specimens at the extremities served as the acceptors, thus producing two acceptor test data results for each test donor detonated. The test separation distance between the donor and the acceptor units was varied from test to test and also within the single test firings during the various exploratory test phases of this program. However, the donor-to-acceptor separation distances were always held constant during the confirmatory test phases.

## Single Projectile, Test Arrangements

The first portion of this safe separation distance study program was confined to the testing of single, unfuzed 155mm M549 HERA Projectiles positioned and aligned to simulate their actual LAP facility conditions during transfer from one loading operation to the next, either between loading station bays or within inter-building tunnels.

The first section of this program portion was an unshielded test array of 155mm M549 HERA Projectiles (fig. 3) with three projectiles arranged in a vertical (nose-up) linear position on a 2.54- by 15.24-cm (1.0- by 6.0-in) pine board. The test projectiles were supported by low density concrete blocks (two under each donor and acceptor projectile) approximately 76.2 cm (30.0 in) above the existing terrain to fully simulate the LAP facility conveyor system. During the exploratory phase of this program section, the separation distances, measured centerline to centerline between the projectile bodies, ranged from 0.76 to 5.33 m (2.5 to 17.5 ft) over a series of 14 test detonations. The unshielded single projectile confirmatory test phase consisted of a series of 25 tests utilizing the same test array as in the exploratory investigations. Conversely, the centerline separation distances were held constant to amass the necessary statistical data in this array.

As in the initial portion, the second section of this program portion employed a shielded test array of 155mm M549 HERA Projectiles (fig. 4) with three projectiles arranged in a vertical (nose-up) position on a 2.54- by 15.24-cm (1.0- by 6.0-in) pine board in a straight line. The test projectiles were again supported by low density concrete blocks (two under each donor and acceptor projectile) approximately 76.2 cm (30.0 in) above the existing terrain to fully simulate the LAP facility conveyor system. In this section, shielding rods were positioned vertically at the halfway distance between the donor and the acceptor. The shielding rods were solid aluminum bars (6061-T6), 7.6 cm (3.0 in) in diameter, and 76.2 cm (30.0 in) in height. They were welded to aluminum base plates 44.1 cm (18.0 in) wide by 1.3 cm (0.5 in) thick and of sufficient length to be placed under both donor and acceptor projectiles. During the exploratory phase of this program section, the separation distances, measured edge to edge on the projectile bodies, ranged from 6.10 to 8.9 cm (2.4 to 3.0 in) over a series of three test detonations. The shielded single projectile confirmatory test phase consisted of a series of 25 tests utilizing the same test array as that in the exploratory investigations. The centerline separation distances were again held constant to compile the necessary statistical data.

## Palletized Projectile, Test Arrangements

The second and final portion of this safe separation distance study program was the testing of palletized 155mm M549 HERA Projectiles positioned and aligned to simulate their actual LAP facility conditions during transfer from the cast loading operation to the funnel pull operation via a conveyor system. Each pallet contained eight projectiles arranged in a 2 by 4 matrix with the narrow ends of the pallet facing each other. Every projectile utilized in this test portion had its nose plug and supplemental charge substituted with a loading funnel, and a cast full of explosive inserted into the nose of the projectile.

Preliminary testing during this program portion was accomplished with an unshielded test array of 155mm M549 HERA Projectiles, eight to a pallet, utilizing one donor pallet and two acceptor pallets per test firing (fig. 5). The pallets were supported at a height of approximately 38.1 cm (15.0 in) above the existing terrain on low density concrete blocks to again simulate the LAP production specifications. During the unshielded phase of this test program, the separation distances, measured from pallet edge to pallet edge, ranged from 0.8 to 9.3 m (2.5 to 30.0 ft) over a series of four exploratory test detonations. There were no confirmatory tests conducted on the unshielded pallet test array.

The second section of this program portion was a shielded pallet test array with eight 155mm M549 HERA Projectiles to a pallet and three pallets arranged in the one-donor-two-acceptor test configuration. However, for this test section, 7.6-cm (3.0-in) diameter and 94.0-cm (37.0-in) long, solid aluminum (6061-T6) bars were utilized for shielding in the majority of the tests. One test employed an aluminum plate 94.0 cm (37.0 in) high by 30.0 cm (12.0 in) wide by 5.1 cm (2.0 in) thick as a shield. The shielding, in all cases, was welded to aluminum base plates 44.1 cm (18.0 in) in width by 1.3 cm (0.5 in) thick and of sufficient length to be placed fully under the nearest pallet of eight projectiles. During the shielded phase of the test program, three shield configurations were observed. First, an aluminum bar was aligned with each row of projectiles on the pallet. Shielding rods were placed by both the donor and acceptor pallets as shown in figure 6. The second shielding configuration utilized four bars in a single solid row located halfway between the donor and acceptor pallets as shown in figure 7. The third shield was a single aluminum plate located between the donor and acceptor pallets. During the shielded phase of this test program, the separation distances, measured from pallet edge to pallet edge, ranged from 0.3 to 3.1 m (1.0 to 10.0 ft)

over a series of 15 exploratory test detonations. The shielded, palletized projectile confirmatory test phase consisted of a series of 33 test detonations utilizing a shield consisting of aluminum bars aligned with each row of palletized projectiles (fig. 6). The edge-to-edge separation distances were held constant to gather the necessary statistical data.

#### Method of Initiation

The donor projectile (initiated sample) was primed with approximately 0.12 kg (4 oz) of Composition C-4 explosive in the fuze well cavity and electrically initiated by an engineer's special J-2 blasting cap. This method of donor initiation insured that the projectile always detonated high order. In both the single projectile and pallet tests, only one projectile was armed and initiated. The close proximity of the eight projectiles on one pallet allowed for sympathetic high order detonation of the whole pallet.

## TEST RESULTS

### General

As previously stated, the determination of safe separation distances during propagation tests of the 155mm M549 HERA Projectile consisted of two distinct and separate portions, which were subdivided into two test sections. Each test section contained an exploratory phase and, when necessary, a confirmatory test phase. The results of these various tests are discussed below.

### Single Projectile, Test Results

#### Unshielded Projectile Tests

A total of 14 unshielded projectile exploratory tests and 26 confirmatory tests were conducted at the National Space Technology Laboratories (NSTL) Station, Mississippi. The results of these tests are shown in table I. The separation distances used in the exploratory tests (nos. 1 through 14 inclusive in table I) ranged from 0.76 to 5.33 m (2.5 to 17.5 ft) with high order propagations occurring up to 0.76 m (2.5 ft). Based on post-test examinations of the damaged acceptor projectiles, a 1.5-m (5.0-ft) spacing was selected as the minimum non-propagation safe separation distance for confirmatory tests. This distance was confirmed by conducting 26 test detonations (nos. 15 through 40 inclusive in table I). Figures 8, 9 and 10 are views of the unshielded test results. Note the unburned cast composition within the projectile bodies in figures 8 and 9, and the fragment impacts and body crack in figure 10. Specifically, figure 10 is a blow-up photograph of the upper projectile body in the left portion of figure 9.

#### Shielded Projectile Tests

A total of four shielded projectile exploratory tests and 25 confirmatory tests were conducted. The results of these tests are shown in table II. The separation distances used in the exploratory tests (nos. 1 through 4 inclusive in table II) ranged from 8.9 to 61.0 cm (3.5 to 24.0 in) without high order propagations. Since 8.0 cm (3.5 in) was the closest spacing that could be achieved utilizing the 7.6-cm (3.0-in) shielding bar, it was selected for use in the confirmatory tests. This distance was confirmed by conducting 25 test detonations (nos. 5 through 29 inclusive in table II). Figure 11 is a view of test results

depicting segments of broken shielding bars in the right foreground.

### Palletized Projectile, Test Results

Four exploratory tests on unshielded pallets, containing eight 155mm M549 HERA Projectiles with cast loading funnels, were conducted. The results of these tests are shown in table III, nos. 1 through 4 inclusive. The separation distances used during these tests varied from 0.8 to 9.1 m (2.5 to 30.0 ft) with high order detonations occurring below 0.5 m (5.0 ft). Due to heavy acceptor damages encountered at 3.1 m (10.0 ft) and less, the unshielded testing was discontinued and no confirmatory test phase was conducted. Figure 12 is a post procedural view of these tests. Note the fragment impacts and penetrations on the projectiles.

A total of 11 shielded exploratory pallet tests (nos. 5 through 15 inclusive in table III) were conducted. There were three types of shielding utilized; specifically, (1) two rows of two rods, (2) one row of four rods [all rods (aluminum) were 7.6 cm (3.0 in) in diameter], and (3) an aluminum plate. The separation distances during the shielded exploratory tests varied from 0.3 to 3.1 m (1.0 to 10.0 ft) with high order detonations occurring at distances of 2.2 m (7.0 ft) and less. A total of 33 confirmatory tests were conducted (nos. 16 through 48 inclusive in table III) utilizing the double row of two bars as a shield and the 3.1-m (10.0-ft) separation distance. Figure 13 is a post procedural view of this phase. Note the lack of damage to the projectile, while the shielding bar in the background has many fragment impacts.

### Summary of Test Results

#### Single Projectile Tests

The single projectile safe separation distance for 155mm M549 Projectiles was established as 1.5 m (5.0 ft) measured centerline to centerline. After discussion with appropriate LAP personnel, it was determined that this distance was not compatible with existing equipment and would severely disrupt necessary production rates. To compensate for this disparity, an attempt was undertaken to reduce this distance using shields. Specifically, a second series of safe spacing tests were conducted utilizing 7.6-cm (3.0-in) diameter aluminum (6061-T6) bars as shields, positioned vertically in a straight line halfway between the donor and acceptor projectiles. The confirmatory test results with this form of shielding clearly indicated that

no propagation of detonations occurred at a spacing of 8.9 cm (3.5 in) measured edge to edge. This was the minimum spacing necessary utilizing a 7.6-cm (3.0-in) diameter shield.

#### Palletized Projectile Tests

A minimum series of unshielded exploratory tests revealed that pallets of eight projectiles (still in 2 by 4 matrices) required safe separation distances in excess of facility spacing limitations. Analysis of acceptor projectile fragment damage indicated the potential of donor detonation propagation at distances of 9.1 m (30.0 ft). Subsequently, this series was discontinued in favor of shielded pallet tests. The shielded pallet tests utilized identical aluminum bars as those used in the single projectile tests. The bars were arranged in various configurations (two rows of two bars and one row of four bars) in conjunction with a single aluminum plate 5.1 cm (2.0 in) thick. The confirmation tests were conducted with two aluminum (6061-T6) bars 7.6 cm (3.0 in) in diameter serving as shields, aligned with the projectile centerline on the ends of each pallet. This shielding system yielded a safe separation distance of 3.1 m (10.0 ft).

#### Analysis of Test Results

Variations in manufacturing tolerances, materials, wear, etc., require that statistical methodology be employed in the interpretation of the confirmatory test data. The actual probability of a continuous propagation caused by an unexpected explosive incident in a LAP facility ammunition production line is a function of the number of propagation occurrences in a particular test phase vs. the total number of test detonations conducted (see Appendix for Statistical Theory).

In the unshielded single projectile confirmatory test phase of this study, there was a total of 53 observations recorded at the 1.5-m (5.0-ft) safe separation distance. Statistically, an upper limit of 6.72 percent probability of propagation of an explosive incident at the 95 percent confidence level was established. The shielded single projectile confirmatory test phase had a total of 52 observations recorded at the 8.9-cm (3.5-in) safe separation distance, using a 7.6-cm (3.0-in) diameter aluminum (6061-T6) bar as a shield between projectiles. This yielded an upper limit of 6.85 percent probability of propagation during an explosive incident at the 95 percent confidence level.

The palletized projectile (8 projectiles per pallet) confirmatory test phase of this study utilized a shielding arrangement consisting of two aluminum bars (same as in single projectile tests) on each end of the pallets and aligned with the projectile's centerline. A total of 66 observations were recorded during this test phase, resulting in an upper limit of 4.8 percent probability of propagation in the event of an explosive incident at the 95 percent confidence level.

Similarly, in a large number of tests, the probability of an unexpected incident propagating to a catastrophic event will be less than, or equal to, the stated values above 95 out of 100. These values reflect the quality of the test results and the reliance that can be placed on the conclusions drawn from the data.

## CONCLUSIONS

It may be concluded from the test results of the single projectile phase that the unshielded safe separation distance between 155mm M549 Projectiles is 1.5 m (5.0 ft). At this distance, the probability of the propagation of an explosive incident is 6.72 percent at the 95 percent confidence level. If a shield, consisting of a single 7.6-cm (3.0-in) diameter aluminum (6061-T6) rod, is positioned vertically in a straight line halfway between the projectiles on a conveyor system in existing loading plants, the safe separation distance will be 8.9 cm (3.5 in). The probability of the propagation of an explosive incident under these conditions is 6.85 percent at the 95 percent confidence level.

Also, it may be concluded from the palletized projectile tests that the safe separation distance between pallets of eight 155mm M549 Projectiles, arrayed in a 2 by 4 matrix, utilizing a shielding arrangement consisting of two 7.6-cm (3.0-in) diameter aluminum (6061-T6) bars on each end of the pallets, and aligned with the projectile's centerline, is 3.1 m (10.0 ft). At this distance, the probability of the propagation of an explosive incident is 4.8 percent at the 95 percent confidence level.

## NOTES

NDP No Detonation Propagation

LOD Propagation to Low Order Detonation

HOD Propagation to High Order Detonation

Light damage Minor shell body cracks from fragment impacts, no full penetrations.

Heavy damage More than 50 percent broken and cracked projectiles with some or all of the exposed explosives and rocket motors burned out.

Table 1. Single round tests (w/o shielding)

Test No.	Separation		Remarks
	m	(ft)	
1	3.05	(10)L	NDP, projectile fragmented
	4.57	(15)R	NDP, few penetrations
2	2.44	( 8)L	NDP, projectile fragmented
	3.05	(10)R	NDP, projectile fragmented, rocket motor ignited and propelled fragment 139 m (456 ft)
3	3.81	(12.5)L	NDP, many penetrations
	4.57	(15)R	NDP, projectile fragmented
4	1.52	( 5)L	NDP, projectile fragmented
	6.10	(20)R	NDP, minor hits, no penetrations
5	0.76	( 2.5)L	NDP, partial burning of both HE and rocket fuel, projectile fragmented
	5.33	(17.5)R	NDP, major hits, no penetrations
6	0.31	( 1)L	HOD
	4.57	(15)R	NDP, one penetration
7	4.57	(15)L	NDP, minor penetrations and projectile fragmented
	4.57	(15)R	NDP, no penetrations
8	4.57	(15)L	NDP, no penetrations
	4.57	(15)R	NDP, one penetration
9	4.57	(15)L	NDP, no penetrations
	4.57	(15)R	NDP, one penetration
10	4.57	(15)L	NDP, no penetrations
	4.57	(15)R	NDP, one penetration
11	4.57	(15)L	NDP, three penetrations
	4.57	(15)R	NDP, projectile fragmented, rocket motor ignited and propelled fragment 27.5 m (90 ft)

Table 1. Single round tests (w/o shielding)  
(cont'd)

Test No.	Separation m (ft)		Remarks
12	0.76	( 2.5)L	NDP, two penetrations, rocket motor ignited and propelled fragment 3.66 m (36 ft)
	0.76	( 2.5)R	NDP, three penetrations, rocket motor ignited and propelled fragments 2.44 m (8 ft)
13	0.76	( 2.5)L	NDP, two penetrations, projectile body cracked
	0.76	( 2.5)R	NDP, three penetrations, rocket motor partially burned
14	0.76	( 2.5)L	HOD
	0.76	( 2.5)R	HOD
15	1.52	( 5)L	NDP, projectile fragmented, one penetration
	1.52	( 5)R	NDP, five penetrations, rocket motor ignited and propelled fragments 13.7 m (45 ft)
16	1.52	( 5)L	NDP, two penetrations, no burning
	1.52	( 5)R	NDP, four penetrations, rocket burned
17	1.52	( 5)L	NDP, three penetrations, no burning
	1.52	( 5)R	NDP, two penetrations, rocket motor burned
18	1.52	( 5)L	NDP, four penetrations, rocket motor ignited and propelled fragments 31.7 m (104 ft)
	1.52	( 5)R	NDP, four penetrations, rocket motor burned
19	1.52	( 5)L	NDP, one penetration, rocket motor burned
	1.52	( 5)R	NDP, two penetrations, rocket motor ignited and propelled fragments 18.3 m (60 ft)

Table 1. Single round tests (w/o shielding)  
(cont'd)

Test No.	Separation m (ft)		Remarks
20	1.52	( 5)L	NDP, five penetrations, rocket motor burned
	1.52	( 5)R	NDP, three penetrations, rocket motor burned
21	1.52	( 5)L	NDP, three penetrations, rocket motor ignited and propelled fragments 67.7 m (222 ft)
	1.52	( 5)R	NDP, one penetration, rocket motor ignited and propelled fragments 35.7 m (117 ft)
22	1.52	( 5)L	NDP, one penetration, no burning
	1.52	( 5)R	NDP, one penetration, no burning
23	1.52	( 5)L	NDP, three penetrations, no burning
	1.52	( 5)R	NDP, two penetrations, rocket motor burned
24	1.52	( 5)L	NDP, two penetrations, rocket motor burned
	1.52	( 5)R	NDP, six penetrations, rocket motor burned
25	1.52	( 5)L	NDP, one penetration, no burning
	1.52	( 5)R	NDP, three penetrations, rocket motor ignited and propelled fragments 22.9 m (75 ft)
26	1.52	( 5)L	NDP, no penetrations, rocket motor burned
	1.52	( 5)R	NDP, one penetration, rocket motor burned
27	1.52	( 5)L	NDP, three penetrations, rocket motor burned
	1.52	( 5)R	NDP, no penetrations, no burning

Table 1. Single round tests (w/o shielding)  
(cont'd)

Test No.	Separation m (ft)		Remarks
28	1.52	( 5)L	NDP, two penetrations, rocket motor ignited and propelled fragments 64 m (210 ft)
	1.52	( 5)R	NDP, two penetrations, rocket motor burned
29	1.52	( 5)L	NDP, three penetrations, no burning
	1.52	( 5)R	NDP, one penetration, rocket motor ignited and propelled fragments 47.5 m (156 ft)
30	1.52	( 5)L	NDP, five penetrations, no burning
	1.52	( 5)R	NDP, one penetration, rocket motor ignited and propelled fragments 14.9 m (49 ft)
31	1.52	( 5)L	NDP, one penetration, rocket motor ignited and propelled fragments 12.2 m (40 ft)
	1.52	( 5)R	NDP, three penetrations, rocket motor ignited and propelled fragments 19.8 m (65 ft)
32	1.52	( 5)L	NDP, no penetrations, no burning
	1.52	( 5)R	NDP, one penetration, no burning
33	1.52	( 5)L	NDP, five penetrations, rocket motor ignited and propelled fragments 366 m (1,200 ft)
	1.52	( 5)R	NDP, two penetrations, rocket motor burned
34	1.52	( 5)L	NDP, four penetrations, rocket motor burned
	1.52	( 5)R	NDP, four penetrations, no burning
35	1.52	( 5)L	NDP, four penetrations, rocket motor burned
	1.52	( 5)R	NDP, three penetrations, rocket motor ignited and propelled fragments 12.2 m (40 ft)

Table 1. Single round tests (w/o shielding)  
(cont'd)

Test No.	Separation		Remarks
	m	(ft)	
36	1.52	( 5)L	NDP, two penetrations, no burning
	1.52	( 5)R	NDP, four penetrations, rocket motor ignited and propelled fragments 46.3 m (152 ft)
37	1.52	( 5)L	NDP, three penetrations, rocket motor burned
	1.52	( 5)R	NDP, no penetrations, no burning
38	1.52	( 5)L	NDP, one penetration, no burning
	1.52	( 5)R	NDP, no penetrations or burning
39	1.52	( 5)L	NDP, two penetrations, no burning
	1.52	( 5)R	NDP, four penetrations, no burning
40	1.52	( 5)L	NDP, one penetration, rocket motor burned
	1.52	( 5)R	NDP, no penetrations or burning

Table 2. Single round tests (w/shielding)

Shielding consisted of an aluminum bar, 7.6 cm (3.0 in) in diameter and the full height of the loaded projectiles, located at exactly half the separation distance and in line with the projectiles.

Test No.	Separation cm (in)		Remarks
1L	30.5	(12.0)	NDP, no damage
R	61.0	(24.0)	NDP, projectile fragmented
2L	15.2	( 6.0)	NDP, projectile fragmented
R	30.2	(12.0)	NDP, projectile - motor separated
3L	8.9	( 3.5)	NDP, projectile fragmented
R	8.9	( 3.5)	NDP, projectile fragmented
4L	10.2	( 4.0)	NDP, projectile - motor separated
R	10.2	( 4.0)	NDP, projectile fragmented
5L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
6L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
7L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
8L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
9L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
10L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
11L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
12L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP

Table 2. Single round tests (w/shielding)  
(cont'd)

Test No.	Separation		Remarks
	cm	(in)	
13L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
14L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
15L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
16L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
17L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
18L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
19L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
20L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
21L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
22L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
23L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
24L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
25L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
26L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP

Table 2. Single round tests (w/shielding)  
(cont'd)

Test No.	Separation		Remarks
	cm	(in)	
27L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
28L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP
29L	8.9	( 3.5)	NDP
R	8.9	( 3.5)	NDP

Table 3. Pallet tests (8 projectiles per pallet)

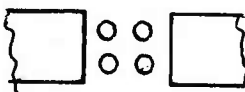
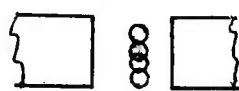
Test No.	Separation m (ft)		Shielding	Remarks
1L	6.2	(20.3)	No	NDP, medium damage
R	9.2	(30.2)	No	NDP, medium damage
2L	1.5	( 5.0)	No	NDP, heavy damage
R	3.1	(10.2)	No	NDP, heavy damage
3L	0.8	( 2.5)	No	HOD
R	1.5	( 5.0)	No	HOD
4L	2.2	( 7.0)	No	NDP, heavy damage
R	2.2	( 7.0)	No	NDP, heavy damage
5L	0.8	( 2.5)		NDP, heavy damage
R	1.5	( 5.0)		NDP, heavy damage
6L	0.8	( 2.5)	Same as #5	NDP, heavy damage
R	0.3	( 1.0)		HOD
7L	0.9	( 3.0)	Same as #5	NDP, heavy damage
R	0.9	( 3.0)		NDP, heavy damage
8L	0.9	( 3.0)	Same as #5	NDP, heavy damage
R	0.9	( 3.0)		NDP, heavy damage
9L	0.9	( 3.0)	Same as #5	NDP, heavy damage
R	0.9	( 3.0)		NDP, heavy damage
10L	0.9	( 3.0)	Same as #5	NDP, heavy damage
R	0.9	( 3.0)		NDP, heavy damage
11L	0.9	( 3.0)	Same as #5	NDP, heavy damage
R	0.9	( 3.0)		NDP, heavy damage
12L	0.9	( 3.0)	Same as #5	NDP, heavy damage
R	0.9	( 3.0)		NDP, heavy damage
13L	0.9	( 3.0)	Same as #5	HOD
R	0.9	( 3.0)		HOD
14L	0.9	( 3.0)		HOD
R	0.9	( 3.0)		HOD

Table 3. Pallet tests (8 projectiles per pallet)  
(cont'd)


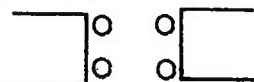
Test No.	Separation m (ft)		Shielding	Remarks
15L	0.9	( 3.0)		HOD
R	0.9	( 3.0)		HOD
16L	3.1	(10.0)		NDP, light damage
R	3.1	(10.0)		NDP, light damage
17L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
18L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
19L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
20L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
21L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
22L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
23L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
24L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
25L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
26L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
27L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
28L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage

Table 3. Pallet tests (8 projectiles per pallet)  
(cont'd)

Test No.	Separation m (ft)		Shielding	Remarks
29L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
30L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
31L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
32L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
33L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
34L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
35L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
36L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
37L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
38L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
39L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
40L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
41L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
42L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage

Table 3. Pallet tests (8 projectiles per pallet)  
(cont'd)

Test No.	Separation m (ft)		Shielding	Remarks
43L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
44L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
45L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
46L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
47L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage
48L	3.1	(10.0)	Same as #16	NDP, light damage
R	3.1	(10.0)		NDP, light damage

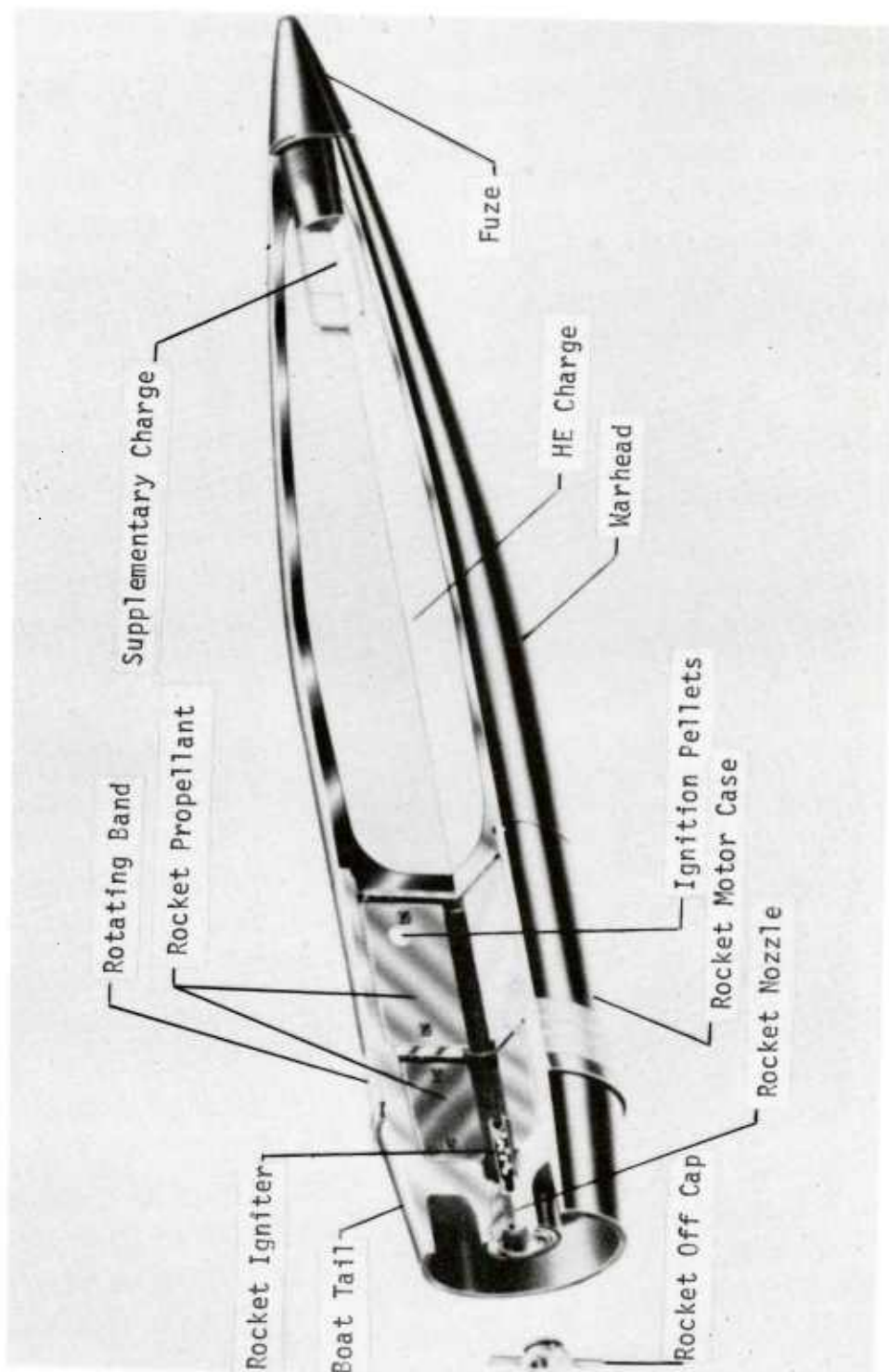


Figure 1. 155mm M549 HERA Projectile cross-section

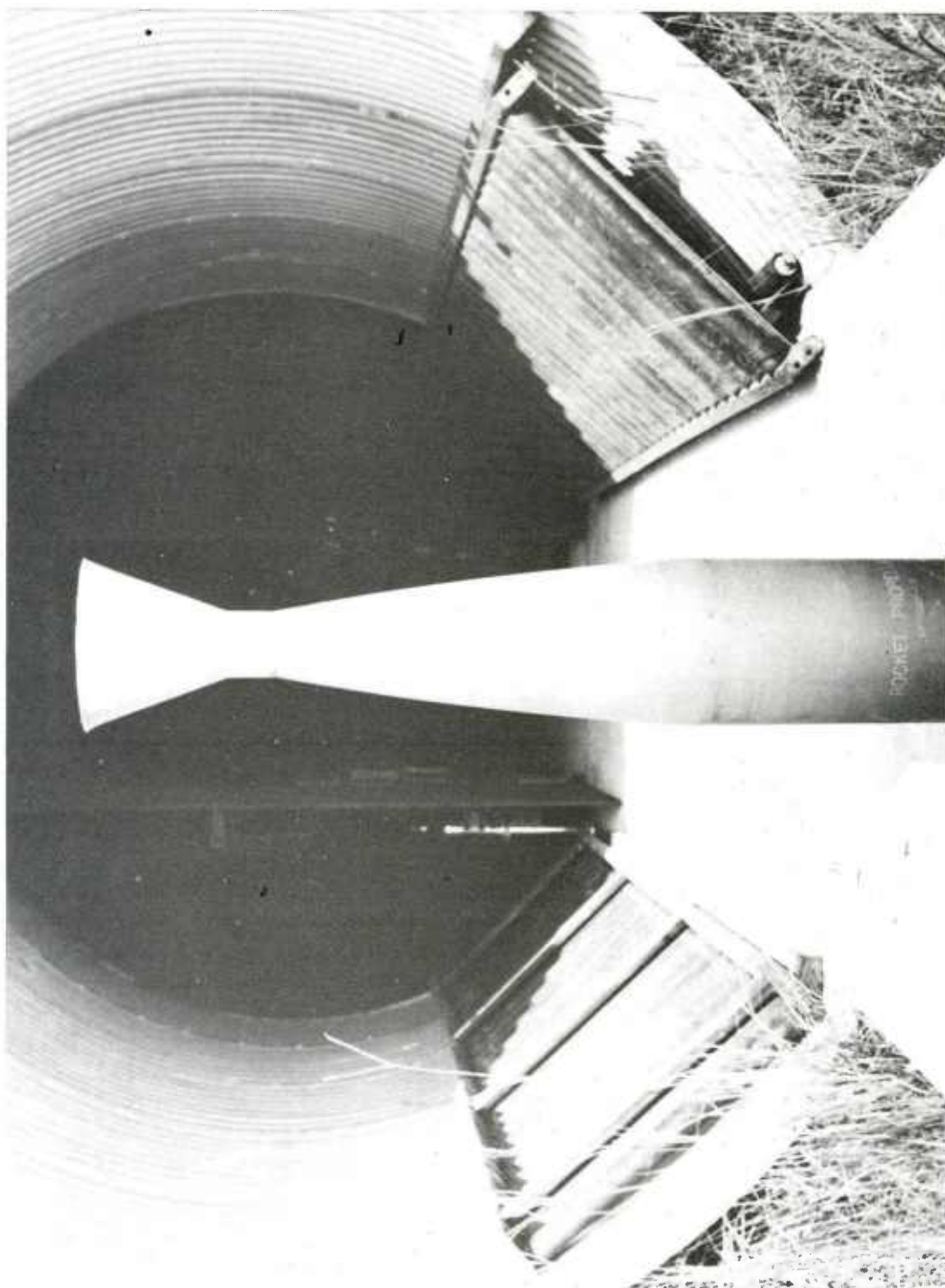


Figure 2. Projectile with loading funnel



Figure 3. Test array, unshielded single projectile



Figure 4. Test array, shielded single projectile



Figure 5. Test array, unshielded pallet

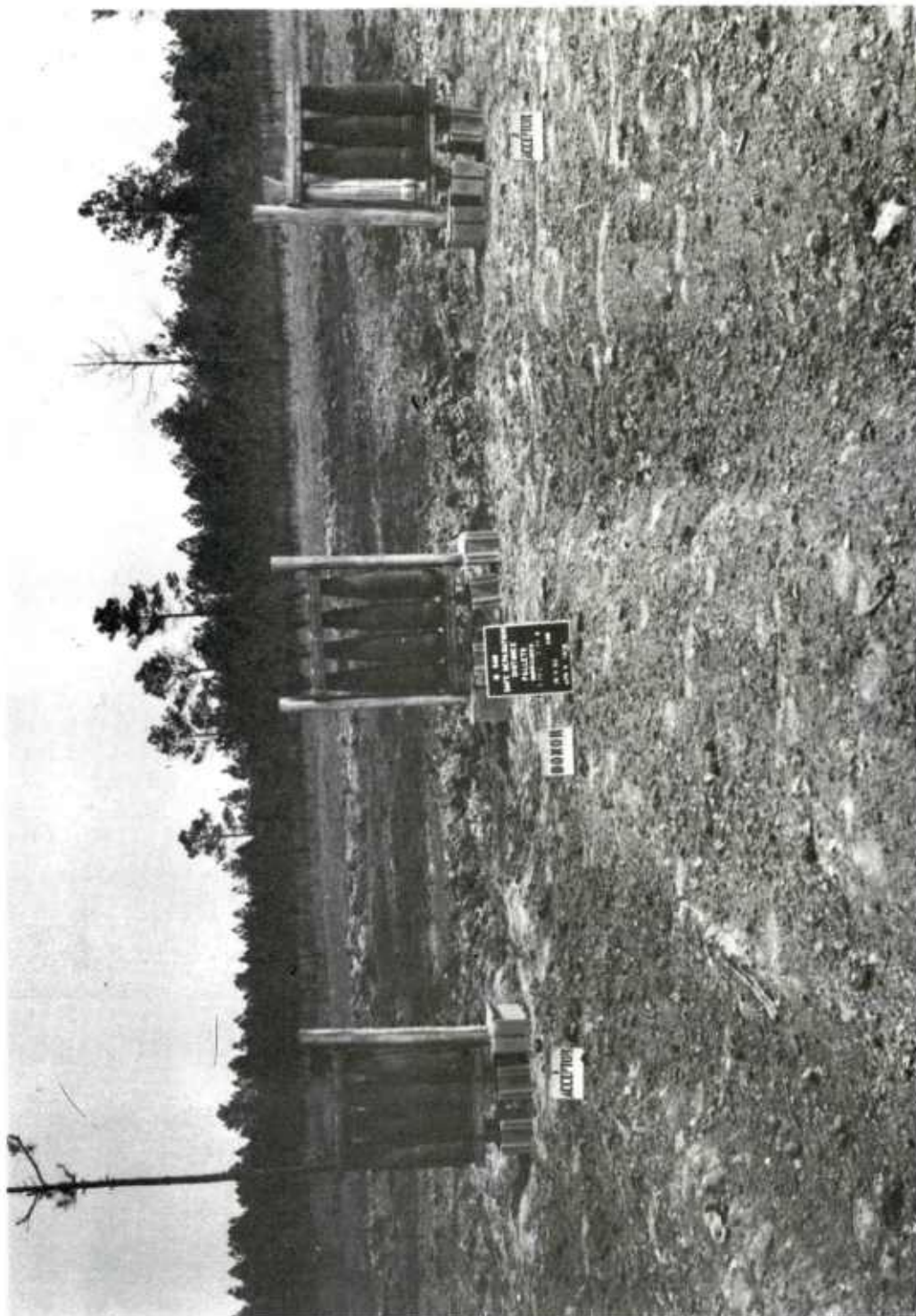


Figure 6. Test array, shielded pallet no. 1

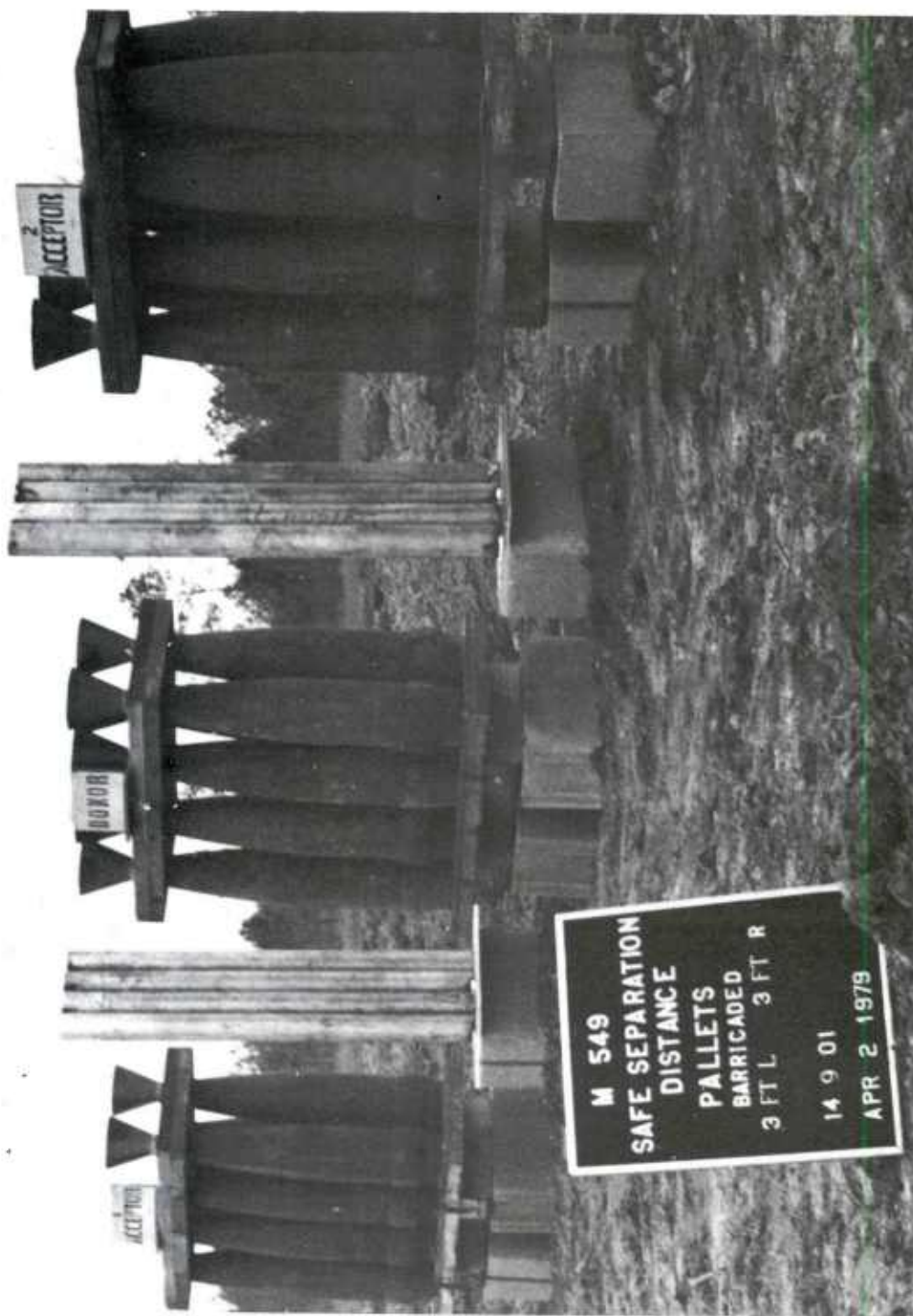


Figure 7. Test array, shielded pallet no. 2



Figure 8. Results, single projectile, unshielded

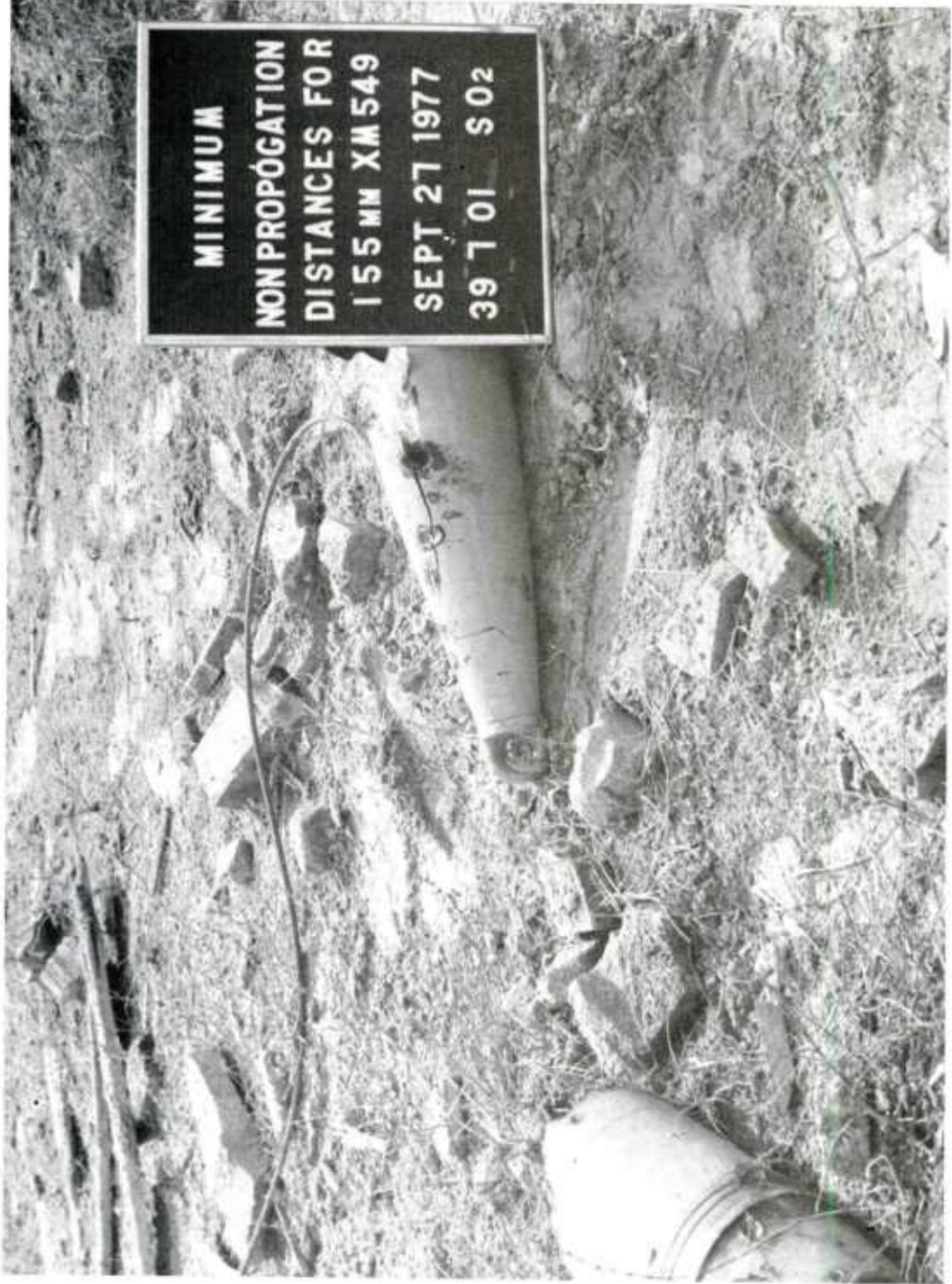


Figure 9. Results, single projectile, unshielded

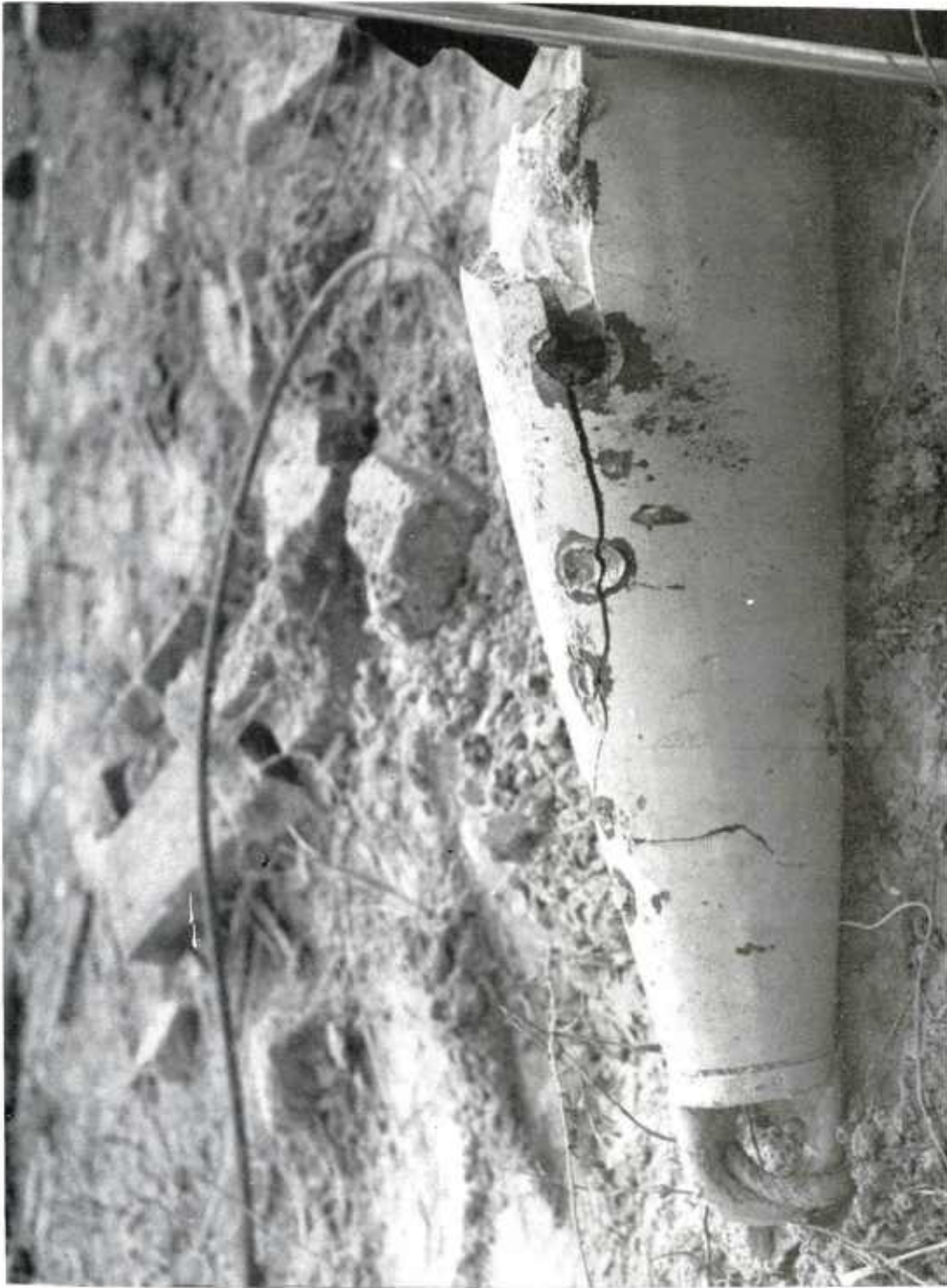


Figure 10. Results, single projectile, unshielded

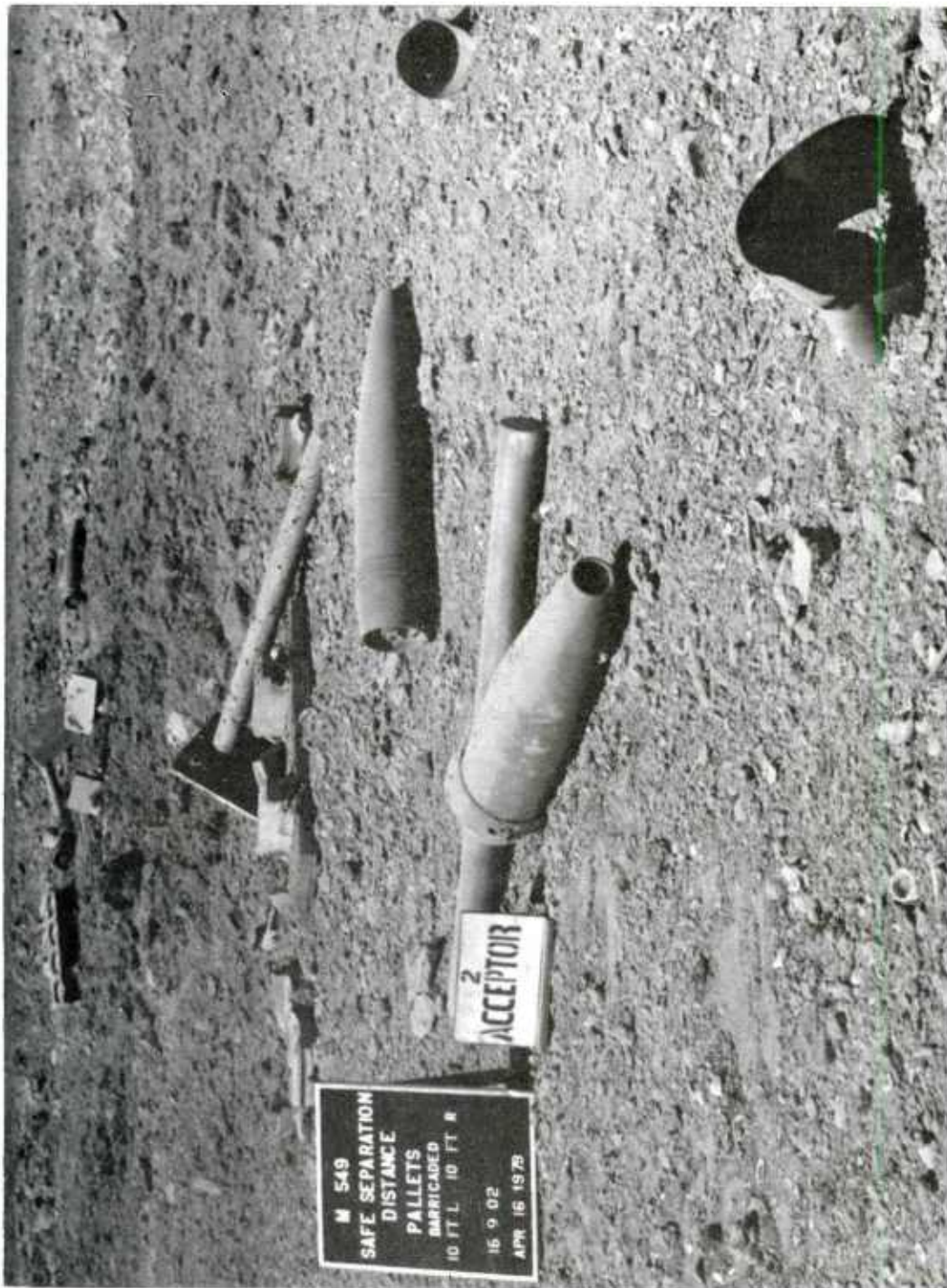


Figure 11. Results, single projectile, shielded

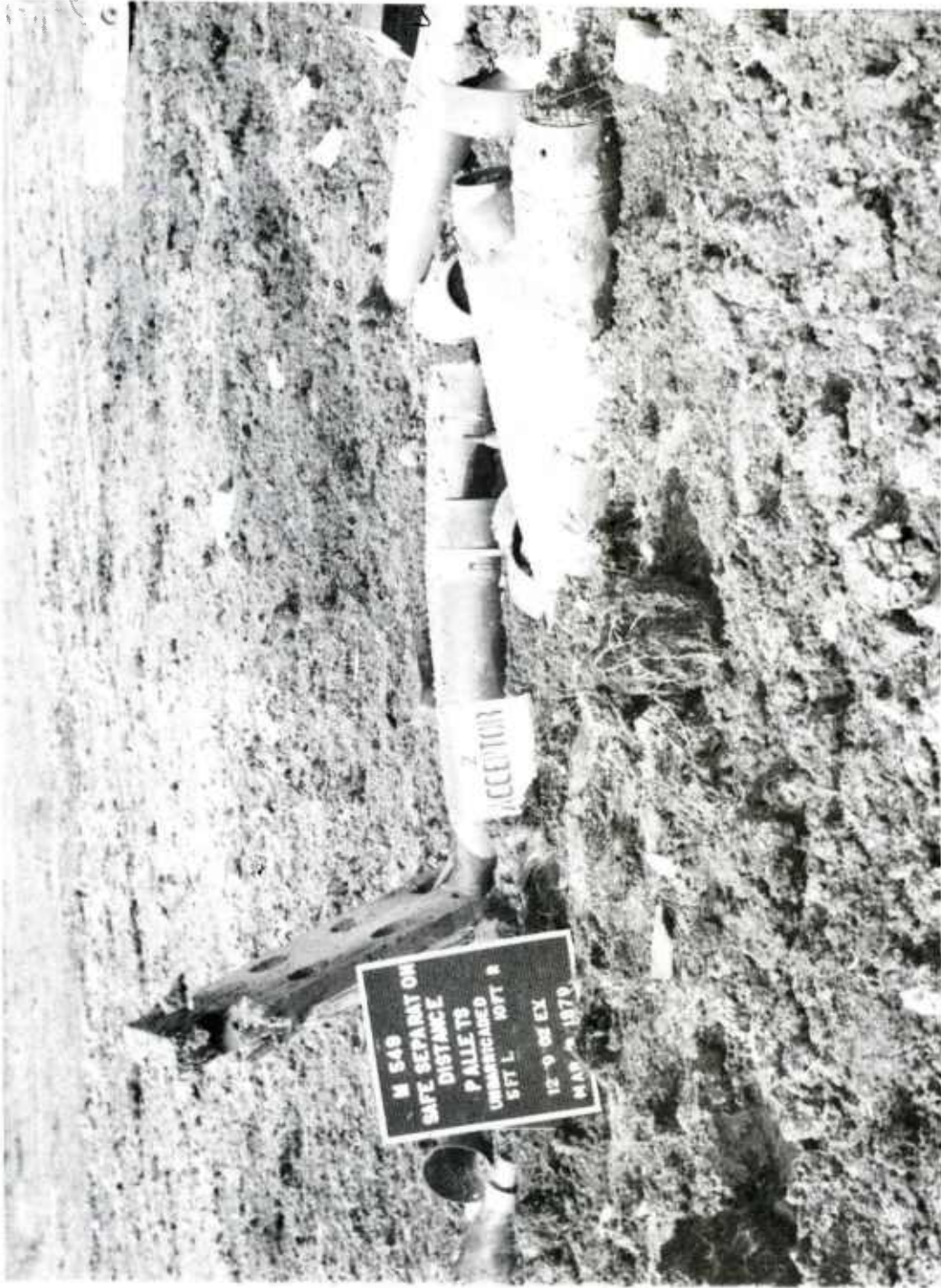


Figure 12. Results, pallet unshielded

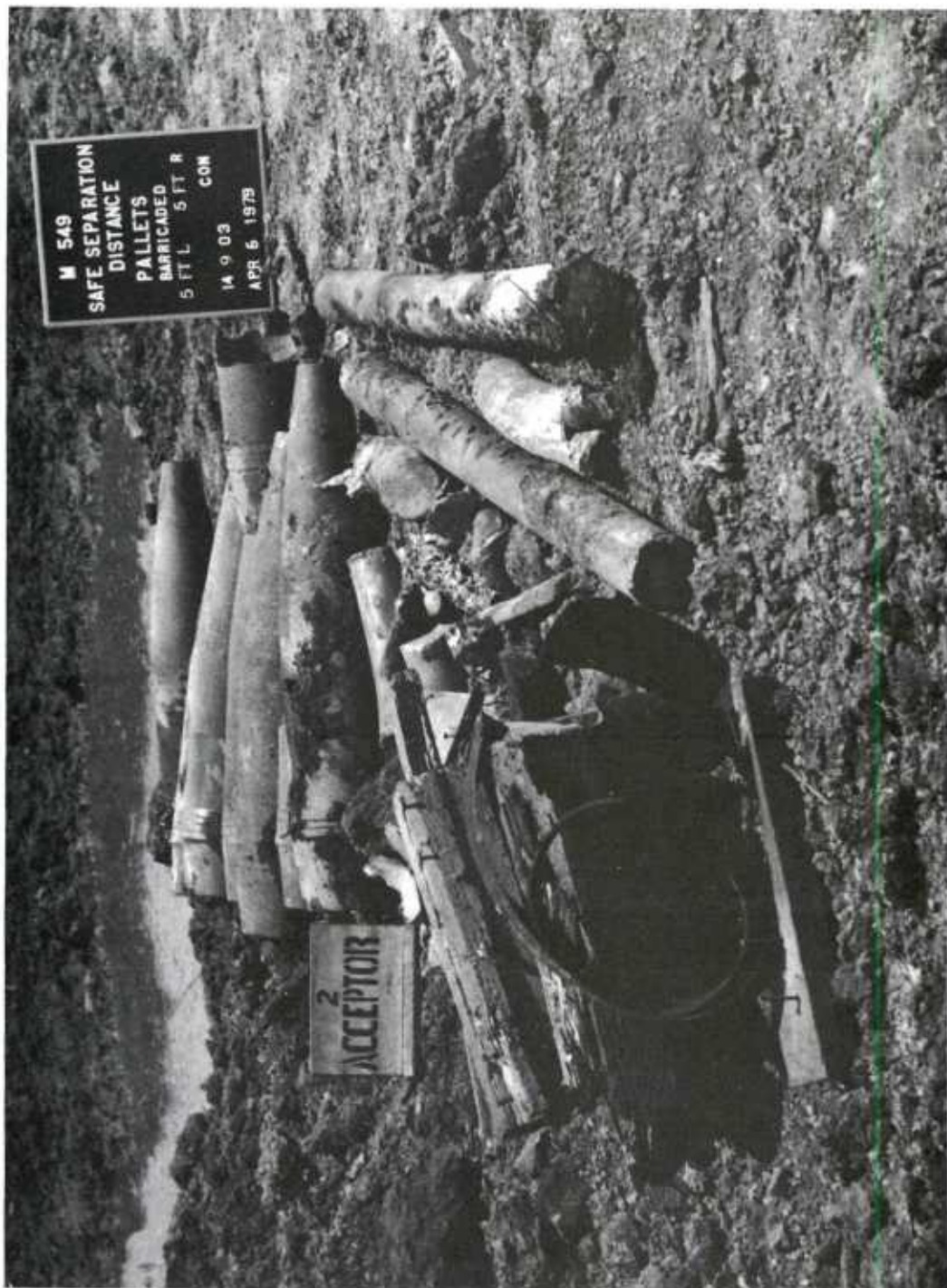


Figure 13. Results, pallet shielded

## APPENDIX

### STATISTICAL EVALUATION OF EXPLOSION PROPAGATION

## STATISTICAL EVALUATION OF EXPLOSION PROPAGATION

### Statistical Theory

The possibility of the occurrence of explosion propagation based upon a statistical analysis of the test results has been evaluated in the main body of the report. This appendix is devoted to the mathematical means by which the statistical analysis was performed.

The probability of the occurrence of an explosion propagation is dependent upon the degree of certainty or confidence level involved and has upper and lower limits. The lower limit for all confidence levels is zero; whereas the upper limit is a function of the number of observations or, in this particular case, the number of acceptor items tested. Since each observation is independent of the others and each observation has a constant probability of a reaction occurrence (explosion propagation), the number of reactions ( $x$ ) in a given number of observations ( $n$ ) will have a binomial distribution. Therefore, the estimate of the probability ( $p$ ) of a reaction occurrence can be represented mathematically by

$$p = x/n \quad (1)$$

and, therefore, the expected value of ( $x$ ) is given by

$$E(x) = np \quad (2)$$

Each confidence level will have a specific upper limit ( $p_2$ ) depending upon the number of observations involved. The upper probability limit for a given confidence level  $\alpha$ , when a reaction is not observed, is expressed as

$$(1 - p_2)^n = \epsilon \quad (3)$$

$$\text{where} \quad \epsilon = (1 - \alpha)/2 \text{ and } \alpha < 1.0 \quad (4)$$

Use of equation 3 is illustrated in the following example:

#### Example

Determine the upper probability limit of the occurrence of an explosion propagation for a confidence level of 95% based upon 30 observations without a reaction occurrence.

### Given

Number of Observations (n) = 30  
Confidence Level ( $\alpha$ ) = 95%

### Solution

1. Substitute the given value of ( $\alpha$ ) into equation 4 and solve for  $\epsilon$ :

$$\epsilon = (1 - \alpha)/2 = (1 - 0.95)/2 = 0.025$$

2. Substitute the given value of (n) and value of ( $\epsilon$ ) into equation 3 and solve for  $p_2$ :

$$\epsilon = 0.025 = (1 - p_2)^{30}$$

or

$$p_2 = 0.116(11.6\%)$$

### Conclusions

For a 95% confidence level and 30 observations, the true value of the probability of explosion propagation will fall between zero and 0.116; or statistically, it can be interpreted that in 30 observations, a maximum of  $(0.116 \times 30) = 3.48$  observations could result in a reaction for a 95% confidence level.

### Probability Table

Table A-1 shows the probability limits and the range of the expected value  $E(x)$  for different numbers of observations. Three confidence limits, 90, 95 and 99%, are used to derive the probabilities. The same values are plotted in Figure A-1.

Table A-1. Probabilities of propagation for various confidence limits

Number of observations	90%		95%		99%	
	p2	C.L. E(x)	p2	C.L. E(x)	p2	C.L. E(x)
n						
10	0.259	2.59	0.308	3.08	0.411	4.11
20	0.131	2.62	0.168	3.36	0.233	4.66
30	0.095	2.85	0.116	3.48	0.162	4.86
40	0.072	2.88	0.088	3.52	0.124	4.96
50	0.058	2.9	0.071	3.55	0.101	5.05
60	0.049	2.92	0.060	3.6	0.085	5.10
80	0.037	2.96	0.045	3.6	0.064	5.12
100	0.030	3.0	0.036	3.6	0.052	5.2
200	0.015	3.0	0.018	3.6	0.026	5.2
300	0.010	3.0	0.012	3.6	0.018	5.4
500	0.006	3.0	0.007	3.5	0.011	5.5

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